Development of a Short-lived Radioisotope Production Service (SRPS) for CTTC at the University of Alberta SLOWPOKE Reactor Facility

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EXECUTIVE SUMMARY

On the basis of a number of criteria proposed by the author 15 radioisotopes (and various water-soluble chemicals) have been identified that would likely meet CTTC needs. In order of increasing half-life the radioisotopes include: ^{165}Dy, ^{56}Mn, ^{171}Er, ^{42}K, ^{64}Cu, ^{72}Ga, ^{142}Pr, ^{24}Na, ^{187}W, ^{76}As, ^{166}Ho, ^{82}Br, ^{140}La, ^{153}Sm, and ^{198}Au. Of these radioisotopes it would be possible to produce sufficient activity with the University of Alberta SLOWPOKE Reactor to provide 100 mCi (3.7 GBq) on-site at the CTTC at Suffield (assuming a decay period of 16h to permit transportation and overnight storage of the radioisotopes prior to use) of each of the above radioisotopes excluding ^{165}Dy, ^{56}Mn, ^{171}Er, and ^{42}K. The low isotopic abundance of ^{41}K limits the activity of ^{42}K that can readily be produced using the University of Alberta SLOWPOKE Reactor and supplied to Suffield to ~ 25 mCi. Similarly, the low isotopic abundance and neutron cross-section of ^{170}Er (the precursor of ^{171}Er) limit the activity of ^{171}Er that could be produced and delivered to Suffield to about 10 mCi (following a decay period of 16 h). Because of the short half-lives of ^{165}Dy and ^{56}Mn, 100 mCi of each radioisotope could be supplied on-site at Suffield if the radioisotopes were collected and transported to Suffield on the same day within ~5 h (*i.e.*, 9:00 AM pick-up and 2:00 PM delivery for immediate use).

Certified Type A shipping containers are commercially available and depending upon the decision whether to ship radioisotopes with an activity of ~ 200 mCi (or more) as Yellow II or III shipments the cost of an appropriate shield will range between $2200 to $5400. For shipping smaller amounts of activity (*e.g.*, ≤ ~ 20 mCi) the cost of a certified container and shield would be < $500.

When considering what additional equipment must be purchased in order to minimize any possible interruptions in the radionuclide production service for CTTC one would need to carry out a cost-benefit analysis to assess the cost of the equipment *vs.* how it would minimize the risk of any interruption in the SRPS. Due to the simplicity of its design the SLOWPOKE nuclear reactor is very reliable and has an excellent operational record (particularly in comparison to other nuclear reactors, both research and power). However, the

University of Alberta SLOWPOKE reactor has been operational for almost 28 years and the failure of a component in the reactor console, the radiation monitoring alarm system, or of a reactor component could interrupt the SRPS for CTTC. At some cost (*ca.* $120,000) the University of Alberta reactor console could be replaced with the new RMC SLOWPOKE designed SIRCIS console, the modular nature of which means that the likelihood of any significant downtime, due to the failure of a component, is considerably reduced. The radiation monitoring alarm system of the SLOWPOKE reactor, also essential for its operation, has required an increasing number of minor repairs in recent years. Interruptions to the operation of the reactor due to these repairs have been minimal, but are likely to become more of a problem with increasing age of the components. To minimize the risk to the SRPS for CTTC the radiation monitoring alarm system of the SLOWPOKE reactor could be completely replaced and upgraded for about $25,000.

The majority of the necessary infrastructure to set-up and operate the SRPS at the University of Alberta SLOWPOKE Reactor Facility is already in place. However, some additional equipment would need to be purchased and/or built to operate the SRPS effectively and to minimize potential exposure to personnel. Furthermore, there are the costs associated with the operation of the SRPS. Additional equipment and materials that would be necessary include: a survey meter, a dose calibrator, a Type A shield (for up to a 200 mCi source), a Type A shield (for ≤ 20 mCi source[s]), chemicals, tongs, *etc.* at a cost of between $ 14,000 - $21,000.

The current production costs for 100 mCi of ^{24}Na, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{165}Dy and ^{56}Mn would be of the order of $1800 - $2200 per radioisotope. The cost of producing sufficient activity to have 10 mCi of any of the same radioisotopes, or ^{42}K, at the CTTC, Suffield would be $400 - $500 per radioisotope (with a reduction for the production of two or more radioisotopes). Finally, to produce ~ 1 mCi of any of the 15 radioisotopes would be ~$250 per radioisotope (again with a reduction for the production of two or more radioisotopes).

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1. INTRODUCTION

This document describes the development of a Short-lived Radioisotope Production Service (SRPS) at the University of Alberta SLOWPOKE Reactor Facility as per Public Works and Government Services Canada (PWGSC) Contract No. W7714-030798/001/SS. The purpose of the SRPS would be to produce radioisotopes for training purposes at the Counter Terrorism Training Centre (CTTC), Defence Research and Development Canada (DRDC) Suffield.

2. BACKGROUND

An integral feature of the radiological training facility at Counter Terrorism Training Centre (CTTC), Defence Research and Development Canada (DRDC) Suffield, Alberta is the capability to work with unsealed radioactive sources (primarily in liquid form). The preferred radioisotopes for such work are those with short half-lives, and the radioactive chemical compounds must be water-soluble.

During the course of a recent NATO Exercise Prototype Response at Suffield, DRDC Ottawa used three such radioisotopes (^{24}Na, ^{42}K and ^{64}Cu) in mCi quantities that were produced at the University of Alberta SLOWPOKE Reactor Facility and transported to Suffield.

For future CTTC work radioactive sources of the order of up to 100 mCi are envisaged. A facility to produce such activities on a routine basis is needed. The purpose of this contract is to achieve the design, and perform a rough costing of the SRPS at the University of Alberta SLOWPOKE Reactor Facility.

3. TASK DESCRIPTION

In the PWGSC contract with the University of Alberta, the contractor was to complete the following tasks:

i. Consult with the Scientific Authority and thence provide a list of those radioisotopes and applicable chemical compounds that will:

   a) Meet the needs of CTTC and
   b) Be readily produced in the reactor.

The prospective isotopes include, but are not limited to, ^{24}Na, ^{82}Br, ^{64}Cu and ^{42}K.

ii. Consult with the Scientific Authority and finalize the isotopic and chemical choices and irradiation criteria.

iii. Determine the availability and cost of an appropriate shield (that can be purchased by or for DRDC) for transporting up to 200 mCi of a single radioisotope **OR** if no commercial shield is readily available design an appropriate shield for transporting up to 200 mCi of a single radioisotope; **AND** in either instance also design a transfer system (from reactor to shield) that will minimize dose to personnel for use with high activity productions.

iv. Determine what additional equipment must be purchased in order to minimize any possible interruptions in the radionuclide production service for CTTC.

v. Give costs for construction and operation of SRPS.

(Annex 'A' of the contract, maybe found on p.38 of this report)

The results of completing these tasks are reported in the following pages.

4. SELECTION OF RADIOISOTOPES AND APPLICABLE CHEMICAL COMPOUNDS

Several criteria need to be considered when selecting radioisotopes[1] that will meet CTTC needs and which can be produced in the University of Alberta SLOWPOKE Nuclear Reactor and are in a suitable chemical form (*i.e.*, compound). These criteria include, in decreasing relative order of importance, the following:

- the radioisotopes have an appropriate half-life ($T_{1/2}$)
- the radioisotopes should readily be produced using the SLOWPOKE reactor
- an absence of the concurrent production of unwanted (generally, but not always, long-lived) radioisotopes from multi-isotopic elements, and/or other elements in compounds utilized
- the radioisotope(s) produced have suitable gamma-ray energies and emission-rates
- the activated compounds need to be water soluble
- the starting compounds should preferably be non- or only mildly toxic
- the starting compounds preferably should not be particularly expensive

Explanations for each of the criteria are described in detail below.

a. Appropriate Half-life

When considering a radioisotope for potential use at the CTTC the half-life ($T_{1/2}$) of the radioisotope under consideration is important for two main reasons. Firstly, the rationale behind utilizing shorter-lived radioisotopes for CTTC training is the avoidance of any long-term contamination (and hence associated radiation hazard) of those areas where the radioisotopes will be used. This consideration places an **upper limit** on the half-life of radioisotopes that might be employed at the CTTC for training purposes. Secondly, during the transportation of radioisotope(s) produced at the University of Alberta SLOWPOKE Facility, Edmonton, Alberta to the radiological training facility at CTTC Defence Research and Development Canada (DRDC), Suffield, Alberta decay of the induced radioactivity will occur. This consideration places a **lower limit** on the half-life of radioisotopes for potential use at the CTTC.

[1] Throughout this report the terms 'radioisotope' and 'radionuclide' are used synonymously. In recent years the term 'radionuclide' has tended to replace the older 'radioisotope' term.

In regards to this lower limit experience has shown that it takes about 5 hours to transport a radioisotope shipment by road from the SLOWPOKE Facility at the University of Alberta to the CTTC at Suffield. In addition, trials to date at the CTTC in Suffield that have utilized radioisotopes produced at the University of Alberta SLOWPOKE Facility have been used the day following their production and shipment from the university, with a total decay time of about 16 h (pick-up time ~16:00 hrs the day of production and utilization at ~08:00 hrs the following day). A radioisotope with a $T\frac{1}{2} \leq 2$ h would decay significantly during a 16 h period. For example, a radioisotope with a $T\frac{1}{2} = 1$ h would decay to less than 0.002% of its initial activity in 16 h. Consequently, to supply the CTTC at Suffield 1 mCi (37 MBq) of a radionuclide with a half-life of one hour (following a decay period of 16 h) would require the production and shipping of approximately 65 Ci (~2400 TBq) of the radioisotope in question. Clearly, from the point-of-view of shielding requirements, radiation safety, licensing, production costs, *etc.*, this is neither practical nor viable.

Assuming a delay of 16 h, from the time of production of a radioisotope to the time of usage at the CTTC, the practical lower limit for the half-life of potentially useful radioisotopes would be about 2 to 2.5 h. For such short half-lives, and a 16 h decay period (*i.e.*, 6 to 8 half-lives), significant decay would occur in a 16 h period limiting the amount of activity that could be supplied onsite. Note, however, if the shipment was produced and collected early in the day (say 09:00 AM) and utilized 5 h later (following transportation by road) then radioisotopes with half-lives as short as 1 to 2 h **could** be considered for training purposes (other criteria being met or satisfied). Practically speaking, if 100 mCi (3.7 GBq) of a radionuclide with half-life of 2 to 2.5 h (*e.g.*, ^{165}Dy or ^{56}Mn) was required on-site for CTTC training it would have to be used on the same day, *i.e.*, produced and shipped for use at CTTC within 5 h. To compensate for the decay of these two radionuclides during the 5 h transportation the activity of ^{165}Dy and ^{56}Mn, at the time of pickup from the University of Alberta SLOWPOKE Facility, would need to be 441 mCi (16.3 GBq) and 383 mCi (14.2 GBq), respectively.

A practical upper limit for the half-life of useful radioisotopes for use at the CTTC, while debatable, would likely be ~ 3 days, *i.e.*, the radioactivity would decay to < 0.1 % of its

initial value within one month. In this way one would avoid long-term contamination (and hence any associated radiation hazard) of those areas where the radioisotopes were utilized.

In summary, for a radioisotope to be produced at the University of Alberta SLOWPOKE Reactor Facility, and be considered useful for training purposes at the CTTC the half-life of the radioisotope must be greater than 2 - 2.5 h, and less than 3 d. (*N.B.* radioisotopes with half-lives of 1 to 2 h can be considered for use if they are produced, shipped and utilized on the same day).

b. Radioisotope Readily Produced Using the SLOWPOKE Reactor

To produce sufficient quantities of a radioisotope to be useful as a tracer for the CTTC training the target element (specifically the target isotope or nuclide) must activate readily. Factors affecting or controlling how readily a particular element activates include the isotopic abundance of the specific isotope of interest, its effective neutron cross-section[2], and the half-life of the radioisotope being produced. Additional factors relate to the irradiation conditions and include the reactor neutron flux and the irradiation time.

Table 1 lists a selection of elements, nuclear reactions, radioactive products, half-lives and the calculated activities that would result from irradiating 1g of the listed elements for 2 h at a neutron flux of 5×10^{11} n cm^{-2} s^{-1} (half maximum power of the SLOWPOKE reactor) and then letting the induced radioactivity decay over a 16 h period (*i.e.*, simulating transportation and overnight storage time). As can be seen from the table there are 18 elements which (on the basis of the half-life of their radioactive products *i.e.*, 2 h $\leq$ T½ $\leq$ 3 d) can be activated in the SLOWPOKE reactor producing significant quantities of radioactivity (*e.g.*, ~1 mCi to ~150 mCi per gram of element).

It is important to note that the activities listed in Table 1 are not the maximum amounts of these radioisotopes that can be produced using the University of Alberta SLOWPOKE Reactor. Larger samples and/or multiple reactor irradiation sites can be employed to increase the amount of radioactivity produced proportionally. Similarly, longer irradiation times (*e.g.*,

[2] The cross-section of an isotope, or nuclide, is the probability that that nuclide will absorb or capture a neutron.

up to *ca.* 10 h at 5 x 10^{11} n cm^{-2} s^{-1}, for example) can also be employed to produce more activity.

For the radioisotopes in Table 1 to meet the needs of CTTC additional criteria, listed below, must be met.

Table 1. Radioisotopes and activities that can readily be produced with the SLOWPOKE nuclear reactor (arranged by increasing half-life).

Element	Reaction	Activity *		Radio-Isotope	Half-life
		(mCi)	(MBq)		
Dy	$^{164}Dy\ (n,\gamma)\ ^{165}Dy$	154.4	5713	^{165}Dy	2.334 h
Mn	$^{55}Mn\ (n,\gamma)\ ^{56}Mn$	11.9	441	^{56}Mn	2.5785 h
Er	$^{170}Er(n,\gamma)\ ^{171}Er$	3.18	117.8	^{171}Er	7.156 h
K	$^{41}K\ (n,\gamma)\ ^{42}K$	0.95	35	^{42}K	12.360 h
Cu	$^{63}Cu\ (n,\gamma)\ ^{64}Cu$	17.9	663	^{64}Cu	12.70 h
Ga	$^{71}Ga\ (n,\gamma)\ ^{72}Ga$	13.0	481	^{72}Ga	14.10 h
Na	$^{23}Na\ (n,\gamma)\ ^{24}Na$	8.13	301	^{24}Na	14.959 h
Re	$^{187}Re\ (n,\gamma)\ ^{188}Re$	101.5	3757	^{188}Re	17.005 h
Pr	$^{141}Pr\ (n,\gamma)\ ^{142}Pr$	26.8	991	^{142}Pr	19.12 h
W	$^{186}W\ (n,\gamma)\ ^{187}W$	31.9	1180	^{187}W	23.72 h
As	$^{75}As\ (n,\gamma)\ ^{76}As$	25.9	957	^{76}As	1.0778 d
Ho	$^{165}Ho(n,\gamma)\ ^{166}Ho$	160	5920	^{166}Ho	1.118 d
Br	$^{81}Br\ (n,\gamma)\ ^{82}Br$	7.90	292	^{82}Br	1.4708 d
La	$^{139}La\ (n,\gamma)\ ^{140}La$	14.4	533	^{140}La	1.6781 d
Sm	$^{152}Sm\ (n,\gamma)\ ^{153}Sm$	137.8	5098	^{153}Sm	1.9285 d
U (Np)	$^{238}U\ (n,\gamma)\ ^{239}U \rightarrow\ ^{239}Np$	13.3	491	$^{239}Np(U)$	2.355 d
Au	$^{197}Au\ (n,\gamma)\ ^{198}Au$	142.5	5271	^{198}Au	2.695 d
Sb	$^{121}Sb\ (n,\gamma)\ ^{122}Sb$	12.9	477	^{122}Sb	2.7238 d
Re	$^{185}Re\ (n,\gamma)\ ^{186}Re$	45.1	1668	^{186}Re	3.7183 d

* Conditions: Element mass: 1 g, Tirr: 7200 s (2 h), Neutron flux: 5 x 10^{11} n cm^{-2} s^{-1}, Tdec: 57600 s (16 h)

c. Absence of the Concurrent Production of Unwanted Radioisotopes

When producing radioisotopes using the University of Alberta SLOWPOKE Nuclear Reactor for use at the CTTC it would generally be desirable to have single radioisotopic sources with nuclear characteristics (*e.g.*, half-life, gamma-ray energies and emission rates) that meet the needs of the CTTC. However, when producing a ***desired*** radioisotope using the SLOWPOKE reactor the irradiation can, in some cases, result in the concurrent production of an ***undesirable***[3] radioisotope(s) for either, or both, of the following reasons:

a) the element producing the desired radioisotope is multi-isotopic, and activation of one (or more) of the other stable isotopes generates unwanted radioactivity
b) activation of other elements making up the chemical compound may occur producing unwanted radioactivity.

In both of the above cases the undesirable radioisotope(s) may be either long- or short-lived in nature.

Table 2 lists examples where irradiation in a nuclear reactor results in the production of more than one radioisotope from a single element. In the first example it can be seen that neutron irradiation of antimony (Sb) results in the production of both ^{122}Sb and ^{124}Sb. On the basis of its half-life ^{122}Sb is suitable for CTTC usage (*i.e.*, 2 h $\leq$ T½ $\leq$ 3 d). However, the half-life of ^{124}Sb (T½ = 60.20 d) being much greater than 3 d disqualifies it from being considered for CTTC use, and therefore because of the intimate association of the two Sb radioisotopes, excludes the use of ^{122}Sb also. The same situation applies for the other two examples in Table 2, though in the case of rhenium the half-life of ^{186}Re is only slightly greater than 3 days and might be considered further. While ^{152m1}Eu was not included in Table 1 it is readily produced in the SLOWPOKE reactor and has a suitable half-life. However, it was omitted from the table, and from further consideration, on account of the concurrent production of the very long-lived ^{152}Eu and ^{154}Eu radionuclidic 'impurities'.

As mentioned above neutron activation of elements, making up a chemical compound, other than the one of interest, may occur producing unwanted radioactivity (*i.e.*, radionuclidic

[3] 'Undesirable' in the sense that the radioisotope does not meet the criteria outlined in this report

'impurities'). Of the ninety naturally occurring elements some seventy of them activate with thermal neutrons from a nuclear reactor and decay with the emission of gamma radiation.[4] Hydrogen, carbon and nitrogen do not activate with thermal neutrons hence compounds made up of these elements do not become radioactive due to activation of these constituents.

Table 2. Examples of the simultaneous production of more than one radioisotope from a single element.

Reaction	T½	Isotopic Abundance	γ-ray Energy (keV) and Intensity
$^{121}Sb(n,\gamma)^{122}Sb$	2.7238 d	57.36 %	564.2 (71 %)
$^{123}Sb(n,\gamma)^{124}Sb$	60.20 d	42.64 %	602.7 (98.26%), 1690.98 (47.79%)
$^{151}Eu(n,\gamma)^{152m1}Eu$	9.3116 h	47.8 %	841.6 (14.2%), 963.4 (11.7%) 121.8 (7.0%)
$^{151}Eu(n,\gamma)^{152}Eu$	13.537 y	47.8 %	121.8 (28.58%), 344.28 (26.5%) 1408.0 (21.0 %)*
$^{153}Eu(n,\gamma)^{154}Eu$	8.593 y	52.2 %	123.1 (40.79%), 1274.4 (35.2%); 723.3 (20.22%)*
$^{187}Re(n,\gamma)^{188}Re$	17.005 h	62.6 %	155.0 (15.1%)
$^{185}Re(n,\gamma)^{186}Re$	3.7183 d	37.4 %	137.16 (9.42%)

* ^{152}Eu and ^{154}Eu have numerous additional, lower intensity γ-rays that have not been listed

Oxygen, another common constituent of many chemical compounds, has three stable isotopes, ^{16}O (99.762 %), ^{17}O (0.038 %), and ^{18}O (0.200 %) but only ^{18}O activates with thermal neutrons *via* the reaction $^{18}O(n,\gamma)^{19}O$. However, because of the short half-life of ^{19}O (26.91 s) any induced activity decays to insignificant levels in a matter of minutes following neutron irradiation. Therefore, activation of oxygen is not of concern. Consequently, the hydrogen, carbon, nitrogen and oxygen components of various chemical compounds (*e.g.*, nitrates, hydrates, carbonates, hydroxides, oxides, *etc.*) will not produce unwanted, undesirable or problematic radioactivity.

[4] Some elements do activate but decay solely by beta decay without the emission of gamma-rays, *e.g.*, ^{32}P, and are not considered in detail in this report.

Conversely, when irradiated in a SLOWPOKE reactor P (^{31}P, θ = 100%) and S (specifically ^{34}S, θ = 4.21%) activate to produce the long-lived radioisotopes ^{32}P and ^{35}S *via* the reactions $^{31}P(n,\gamma)^{32}P$ ($T\frac{1}{2}$= 14.262 d, 100 % decay by β^--emission, β^- E_{max} 1.71 MeV) and $^{34}S(n,\gamma)^{35}S$ ($T\frac{1}{2}$= 87.32 d, 100 % decay by β^--emission, β^- E_{max} 167 keV). If, for example, one irradiated sufficient sodium sulphate (Na_2SO_4) in an inner site of the University of Alberta SLOWPOKE Reactor to produce 740 MBq (20 mCi) ^{24}Na onsite at CFB Suffield (following a decay period of 16 h as described previously) the irradiation would simultaneously produce 106 kBq (2.87 μCi) of ^{35}S. Following a decay period of 10 days the ^{24}Na activity would have decayed to 11 kBq (0.3 μCi) while the longer-lived ^{35}S would have decayed by less than 10% and have a residual activity of 98 kBq (2.65 μCi). Therefore, to avoid problems (*e.g.*, contamination or exposure) where possible the use of compounds/salts of P and/or S (*e.g.*, phosphates, sulphates, sulphides, *etc.*) should be avoided (unless of course ^{32}P or ^{35}S are the principal radionuclide(s) of interest for say β^--spectrometry).

A number of elements of interest for possible usage at the CTTC are available in the form of water soluble chlorides (*e.g.*, NaCl, KCl, REE chlorides, *etc*) and would therefore seem to be potentially attractive starting materials. However, when irradiated in a nuclear reactor ^{38}Cl ($T\frac{1}{2}$ = 37.21 m) is produced *via* the reaction $^{37}Cl(n,\gamma)^{38}Cl$. Chlorine-38 decays with the emission of two intense, high energy gamma-rays at 1642 keV and 2167 keV. Irradiation in inner site of the University of Alberta SLOWPOKE Reactor to produce 740 MBq (20 mCi) ^{24}Na onsite at CFB Suffield (following a decay period of 16 h as described above) would simultaneously co-produce 3.15 GBq (85.1 mCi) of ^{38}Cl activity at the end of irradiation. Because of the short half-life of ^{38}Cl its activity would have decayed to 0.41 MBq (11.1 μCi) following an 8 h decay period. Consequently, it is feasible to irradiate a chloride salt and store the sample decay for sufficient time to let the induced ^{38}Cl activity decay prior to shipping the sample. However, there will obviously be simultaneous decay of the radionuclide(s) of interest and if alternative salts of the element(s) of interest are available, and meet the criteria described in this section, they should likely be utilized used over the chlorides. For example, one could use sodium carbonate (Na_2CO_3), or sodium hydroxide (NaOH), as an alternative to sodium chloride (NaCl), when producing ^{24}Na.

In the case of the irradiation of gold trichloride to produce ^{198}Au (see Table 3) because of the much longer half-life of ^{198}Au (2.695 d) *vs* ^{38}Cl (37.21 m) storing the sample for $\geq$ 8 h following irradiation will permit the induced ^{38}Cl activity to decay to a negligible level while not significantly affecting the activity of the ^{198}Au (*i.e.*, ~ 8 % reduction in the ^{198}Au activity after 8 h decay).

In some instances neutron irradiation of a multi-isotopic element produces not only a desired radionuclide but also generates significant amounts of a shorter-lived, undesirable radionuclide. Relevant examples include the unwanted production of ^{80}Br (T½ = 17.68 m) when producing ^{82}Br (T½ = 35.30 h), and the production of ^{66}Cu (T½ = 5.12 m) when producing ^{64}Cu (T½ = 12.70 h). Because of their short-half lives these undesirable radioisotopes often are significantly more active than the radioisotope(s) of interest. For example, using an inner irradiation site of the SLOWPOKE reactor at the end of the neutron irradiation of a copper sample to produce 10 mCi (370 MBq) ^{64}Cu, the sample will have a ^{66}Cu activity of ~ 48.4 mCi (1790 MBq). Similarly, production of 10 mCi (370 MBq) of ^{82}Br at the end of irradiation will simultaneously produce 1.14 Ci (42.0 GBq) of ^{80}Br. While radioisotope licences often include ^{64}Cu or ^{82}Br they generally do not have the shorter-lived ^{66}Cu and ^{80}Br radioisotopes listed. One means to avoid the production of these unwanted short-lived radioisotopes is to irradiate compounds where the desired target isotope has been enriched at the expense (*i.e.*, depletion) of the stable isotope that leads to the production of the shorter-lived, more active interferent. However, for CTTC use the cost to purchase sufficient quantities of a compound highly enriched in the target isotope of interest would, in most instances, be prohibitive. A far less expensive alternative would be to let the more active, short-lived, problematic radioisotope preferentially decay to insignificant levels while only losing a few percent of the activity of the desired radioisotope. In the above ^{64}Cu example, leaving the sample to decay for 1 h at the end of the irradiation period before attempting to handle or ship it would result in the ^{66}Cu activity decaying from 48.4 mCi (1790 MBq) to 0.01 mCi (0.5 MBq), while the ^{64}Cu activity would decrease by less than 6 % of its initial activity to 9.47 mCi (350 MBq). In the case of the ^{82}Br production example above, over a 4 h decay period the 1.14 Ci (42.0 GBq) ^{80}Br activity would decay to $\leq$ 0.1 mCi (3.7 MBq) while the ^{82}Br would decay from 10.0 mCi (370 MBq) to 9.24 mCi (342

MBq). This approach of letting the excessive, unwanted shorter-lived radioactivity decay preferentially is accomplished safely by turning off the reactor at the end of the designated irradiation time while leaving the sample(s) in the reactor. Sometime later, when the unwanted radioactivity has decayed, the sample(s) can be ejected. In this manner one uses the shielding and configuration of the reactor to avoid the risk of unnecessary exposure.

A special case of the production on unwanted radionuclides during the production of a potentially desirable radionuclide occurs when irradiating uranium to produce ^{239}Np ($T\frac{1}{2}$ = 2.355 d) *via* the nuclear reaction ^{238}U (n,γ) ^{239}U $\rightarrow$ ^{239}Np (Table 1). In this reaction ^{239}U decays by beta-emission, with a half-life of 23.45 m, to the longer-lived ^{239}Np. The conversion to ^{239}Np of >99.9% of all the generated ^{239}U will occur within 4 hrs of the end of irradiation. However, during the irradiation of the uranium sample fission of trace amounts of ^{235}U (natural isotopic abundance 0.720 %) in the uranium will result in the production of numerous radioactive fission products with a broad range of half-lives. While irradiation of uranium depleted in ^{235}U would reduce the problem it would not eliminate it, as 'depleted' uranium is not free of ^{235}U. Typically 'depleted' uranium contains ca. 0.2 % ^{235}U. *N.B.* the radiotoxicity of uranium (natural and depleted) is considered slight, or low, while that of ^{239}Np is considered moderate. Production and use of radioisotopes with Z > 89 (*e.g.*, ^{239}Np) generally require amendments to radioisotope licences, etc. Consequently, it is suggested that for CTTC training purposes the use of ^{239}Np not be considered further unless there is a compelling reason otherwise.

d. Suitable Gamma-Ray Energies and Emission Rates

Depending upon the objectives of the CTTC training program(s) utilizing radionuclides produced at the University of Alberta SLOWPOKE Reactor Facility, the energy and intensity of gamma rays produced by the decay of the radionuclide(s) could be of importance. If an exercise is to involve the detection and/or identification of radioactive contaminated material covered by several (*e.g.*, 5-10) centimetres of soil or concrete, for example, then the choice of a radionuclide that only produces low energy gamma-rays may be inappropriate. In such an example, the low energy gamma-rays from ^{166}Ho (80.57 keV), ^{165}Dy (94.7 keV) or ^{153}Sm (69.7 and 103.2 keV) would suffer significant attenuation by overlying material while high

energy gamma-rays from ^{24}Na (1368 keV and 2754 keV) would be attenuated far less (see Table 3 for γ-ray energies and intensities). If however, an exercise involved using gamma-ray spectrometers to locate surface (or near surface) contamination and identify the radionuclides responsible for the contamination, then radioisotopes such as ^{166}Ho, ^{165}Dy and ^{153}Sm might well be suitable choices for testing the thoroughness of an investigator.

There are some important radiation protection and economic benefits associated with using radionuclides that emit mid- to low-energy[5] gamma-rays. High energy gamma-rays, produced by the decay of ^{24}Na, for example (Table 3), are extremely penetrating and therefore require significantly more shielding than mid- to low-energy gamma-ray emitting sources. This has an impact on the size (and cost) of the shipping container/shield needed for transporting the radioisotope(s), the potential exposure to those involved in transporting the radioisotope(s) and the ease of handling of the radioactive package. The thickness of shielding and hence mass, of a shield necessary to transport 370 MBq of ^{24}Na is significantly greater than that required to transport the same activity of ^{166}Ho, ^{165}Dy or ^{153}Sm, for example (see Table 3).

From an examination of Table 3 it is apparent that the majority of the radioisotopes listed emit γ-rays suitable in energy and intensity for CTTC use.

e. Soluble Compounds

It is the understanding of the author that the solid compounds made radioactive using the University of Alberta SLOWPOKE Reactor will subsequently be dissolved and diluted for use at the CTTC. That the activated compound is readily soluble (preferably in a solvent such as water) is therefore essential. As can be seen in Table 3, with the exception of As(III)-oxide, all of the chemical compounds listed are very soluble in water. The insolubility of certain compounds in water (*e.g.*, REE oxides) precludes their use in liquid form at the CTTC without resorting to 'hot' chemistry. Given the availability of alternative soluble REE compounds, such as REE-nitrates or -hydroxides, such chemical manipulations are unnecessary and can be avoided.

[5] For the purposes of this report low, mid- and high energy γ-rays are arbitrarily defined as those ≤ 200 keV, 200 to ~1000 keV, and > 1000 keV, respectively.

In addition to the solubility of the chemicals in water one also needs to consider the properties of the radioactive solution produced by dissolving the irradiated compound in water. Dissolving sodium hydroxide (NaOH) in water results in a strongly basic, corrosive solution. However, such a solution can readily be neutralized by the addition of sufficient dilute hydrochloric acid (HCl), for example, producing extremely soluble sodium chloride (NaCl, 'salt') and water (Eqn. 1).

$$NaOH + HCl = NaCl + H_2O \quad \ldots\ldots (1)$$

For example, if 5 g of activated NaOH was to be dissolved in 500 mL of water one would carefully dissolve the 5 g of NaOH in 479.8 mL of water and subsequently add 20.2 mL of 6.2 N HCl to produce 500 mL of a neutral (pH = 7) solution.

Hydroxides of potassium (KOH) and the REEs (*e.g.*, $La(OH)_3$) can be neutralized in the same manner. Alternatively, different salts or other compounds of the metals can be irradiated. However, as can be seen in Table 4 the weight percent of an element of interest in hydroxide-form (*e.g.*, NaOH or KOH) is significantly greater than in a carbonate or nitrate of the same metal. Therefore, more sample and/or a longer irradiation time must be used to produce the same activity that would result from the irradiation of the hydroxide. For example, there is almost twice as much K in KOH than in KNO_3, and ~25% more Na in NaOH than in Na_2CO_3.

f. Preferably Starting Compounds Non- or Only Mildly Toxic

To avoid the risks associated with the use of particularly toxic chemicals where possible one should avoid the use of highly toxic elements or compounds (*e.g.*, thallium salts). The majority of compounds listed in Table 3 (and 4) are not however, particularly toxic. However, those handling chemicals used for radioisotope production are advised to review the Material Safety Data Sheet (MSDS) for the chemicals in questions and to be familiar with the toxicity, and any other hazards associated with them. The poor solubility of arsenic(III) trioxide, together with concerns over its toxicity, might well preclude it from further consideration at the CTTC.

In addition to the chemical toxicity of the particular compound or element, one should also be aware of the radiotoxicity of the radioisotopes selected for use at the CTTC. All of the radioisotopes in Tables 3 and 4 are classified in the 'moderate radiotoxicity' category (the second lowest category in a four-level classification system, namely, 'very high', 'high', 'moderate' and 'low' radiotoxicity).

g. Preferably Starting Compounds Not Particularly Expensive

Ideally the cost of the compounds used in the production of radioactive tracers for the DRDC training at the CTTC should be a small component of the total of the radionuclide production and shipping costs. A number of factors affect the cost of a chemical including, for example, its element constituents, purity, and availability (supply and demand). Table 4 lists the current cost (2003-2004 Aldrich Catalog) of various chemicals for possible use in radionuclide production for CTTC together with the calculated 'cost/g' for each chemical of stated purity. Typically, only a few grams (or less) of any of the chemicals would be used in a particular production run, or if a significant amount of activity (*e.g.*, 100-200 mCi) was required at most a few tens of grams would be utilized. From Table 4 it can be seen that the cost for the majority of the chemicals listed is < \$1 per g, and only a few compounds cost more than \$10 per g. The most significant exception is the price per g of gold trichloride. However, to produce 10.0 mCi ^{198}Au, utilizing the irradiation conditions outlined in Table 1, would only require 55 mg $AuCl_3$ (*i.e.*, \$6.68 or \$10.12, respectively of the 99% and 99.99+% purity $AuCl_3$).

When considering the use of the rare earth elements, REE (La, Sm, Pr, Dy, Ho and Er) the purity of the chemical is particularly important. The REE behave in a chemically coherent manner and are notoriously difficult to separate from their neighbours. If La is not very well separated from its immediate neighbour Ce, irradiation of this impure La salt, will in addition to the desired production of ^{140}La ($T_{1/2}$= 40.2744 h), result in the unwanted production of ^{141}Ce ($T_{1/2}$= 32.501 d). Similarly, irradiation of an impure Sm salt will result in the production of the long-lived Eu radionuclides ^{152}Eu ($T_{1/2}$= 13.537 y) and ^{154}Eu ($T_{1/2}$= 8.593 y).

Table 3. Radioisotopes, chemicals, formulae and their solubility in water, for possible CTTC use that can readily be produced using the University of Alberta SLOWPOKE Nuclear Reactor.

Radio-isotope	Half-Life	γ-ray Energy (keV)	γ-ray Intensity	Chemical Name	Chemical Formula	Solubility (in water)
^{165}Dy	2.334 h	94.7	3.58 %	Dysprosium nitrate	$Dy(NO_3)_3 \cdot 5H_2O$	very soluble
^{56}Mn	2.5785 h	846.8	98.9 %	Manganese nitrate	$Mn(NO_3)_2 \cdot 4H_2O$	very soluble
		1810.8	27.2 %	Manganese acetate	$Mn(C_2H_3O_2)_2$	very soluble
		2113.1	14.3 %			
^{171}Er	7.516 h	308.31	64.4 %	Erbium nitrate pentahydrate	$Er(NO_3)_3 \cdot 5H_2O$	very soluble
		295.9	28.9 %	Erbium acetate hydrate	$Er(C_2H_3O_2)_3 \cdot xH_2O$	very soluble
		111.62	20.5 %			
		124.01	9.1 %			
^{42}K	12.360 h	1524.7	18.0 %	Potassium nitrate	KNO_3	very soluble
				Potassium hydroxide	KOH	very soluble
				Potassium carbonate	K_2CO_3	very soluble
				Potassium bicarbonate	$KHCO_3$	very soluble
^{64}Cu	12.700 h	511.0	17.4 %	Copper nitrate	$Cu(NO_3)_2 \cdot 2.5H_2O$	very soluble
		1345.8	0.473 %			
^{72}Ga	14.10 h	834.0	96 %	Gallium nitrate	$Ga(NO_3)_3 \cdot xH_2O$	very soluble
		2201.7	25.9 %			
		630.0	24.8 %			
		2507.8	12.78 %			

Table 3. Radioisotopes, chemicals, formulae and their solubility in water, for possible CTTC use that can readily be produced using the University of Alberta SLOWPOKE Nuclear Reactor.

Radio-isotope	Half-Life	γ-ray Energy (keV)	γ-ray Intensity	Chemical Name	Chemical Formula	Solubility (in water)
^{72}Ga	14.10 h	894.3	9.88 %			
		2491.0	7.68 %			
		1050.9	6.91 %			
^{24}Na	14.959 h	1368.6	100 %	Sodium hydroxide	NaOH	very soluble
		2754.0	99.94 %	Sodium carbonate	Na_2CO_3	very soluble
^{142}Pr	19.12 h	1575.9	3.7 %	Praseodymium nitrate	$Pr(NO_3)_3 \cdot 6H_2O$	very soluble
^{187}W	23.72 h	685.8	27.3 %	Ammonium metatungstate	$(NH_4)_6H_2W_{12}O_{40} \cdot xH_2O$	very soluble
		479.5	21.8 %	Ammonium paratungstate	$(NH_4)_{10}H_2(W_2O_7)_6 \cdot xH_2O$	very soluble
		72.0	11.14 %			
		134.2	8.85 %			
		618.4	6.28 %			
^{76}As	1.0778 d	559.10	45.0 %	Arsenic trioxide	As_2O_3	poorly sol' *
		657.04	6.2 %	Arsenic pentoxide	As_2O_5	very soluble
		1216.10	3.42 %			
^{166}Ho	1.115 d	80.57	6.71 %	Holmium acetate hydrate	$Ho(C_2H_3O_2)_3 \cdot xH_2O$	very soluble
^{82}Br	1.4708 d	776.5	83.5 %	Ammonium bromide	NH_4Br	very soluble
		554.3	70.8 %			
		619.1	43.4 %			

Table 3. Radioisotopes, chemicals, formulae and their solubility in water, for possible CTTC use that can readily be produced using the University of Alberta SLOWPOKE Nuclear Reactor.

Radio-isotope	Half-Life	γ-ray Energy (keV)	γ-ray Intensity	Chemical Name	Chemical Formula	Solubility (in water)
^{82}Br	1.4708 d	698.4	28.49 %			
		1044.0	27.23 %			
		1317.5	26.48 %			
		827.8	24.03 %			
		1474.9	16.32 %			
^{140}La	1.6781 d	1596.2	95.4 %	Lanthanum nitrate	$La(NO_3)_3 \cdot 6H_2O$	very soluble
		487.0	45.5 %	Lanthanum nitrate	$La(NO_3)_3 \cdot xH_2O$	very soluble
		815.8	23.3 %	Lanthanum hydroxide	$La(OH)_3$	very soluble
		328.8	20.3 %			
		925.2	6.90 %			
		867.8	5.50 %			
		751.6	4.33 %			
^{153}Sm	1.9285 d	103.2	30.0 %	Samarium nitrate	$Sm(NO_3)_3 \cdot 6H_2O$	very soluble
		69.7	4.85 %	Samarium acetate	$Sm(C_2H_4O_2)_3 \cdot xH_2O$	very soluble
^{198}Au	2.695 d	411.8	96 %	Gold trichloride	$AuCl_3$	very soluble

(* Solubility of As_2O_3 = 1.2 g / 100 mL cold water; solubility of As_2O_5 = 150 g in 100 mL cold water)

Production of ^{142}Pr with impurities of the neighbouring Ce and Nd, would result in the production of ^{141}Ce ($T_{1/2}$= 32.501 d) and ^{147}Nd ($T_{1/2}$= 10.98 d). Irradiation of a dysprosium salt to produce ^{165}Dy could result in the generation of trace long-lived activity from Tb (*e.g.*, ^{160}Tb, $T_{1/2}$= 72.3 d) and Ho (^{166}Ho, $T_{1/2}$= 26.83 h), both neighbouring elements of Dy. Using La as an example, consider the irradiation of a La-salt that was 99% pure La, with Ce being the 1% impurity. Production of 370 MBq (10.0 mCi) ^{140}La (following a decay period of 16 h as in previous examples) would result in the production of 125 kBq (3.37 μCi) ^{141}Ce. Production of the same activity of ^{140}La from a La salt that was 99.99 % pure (*i.e.*, 0.01 % Ce) would result in the production of 1.25 kBq (0.03 μCi) ^{141}Ce activity.

In summary, the use of higher purity chemicals for radioisotope production is recommended to avoid the production of any unwanted long-lived activity from chemical impurities. This is particularly the case when producing the REE radioisotopes listed in Table 3. In most instances the cost of the chemicals used to produce the envisaged amount of activity of the various radioisotopes for CTTC use will, in most instances, be ≤ ~$30 per radioisotope production run, *i.e.*, < 1% - 2 % of the actual production costs.

Table 4. Data on composition, purity and cost of chemicals for radioisotope production for CTTC.

Chemical Name	Chemical Formula	Wt % Element of Interest	Purity (%)	Mass (g)	Price (CAN $)	Price ($/g)
Ammonium metatungstate	$(NH_4)_6H_2W_{12}O_{40} \cdot xH_2O$	≤ 73 %	99.99	100	$ 79	$ 0.79
Ammonium paratungstate	$(NH_4)_{10}H_2(W_2O_7)_6 \cdot xH_2O$	≤ 72 %	99.99	50	$ 271	$ 5.42
Manganese nitrate	$Mn(NO_3)_2 \cdot 4H_2O$	11 %	99.99	100	$ 370	$ 3.70
Manganese acetate	$Mn(C_2H_3O_2)_2$	18.5 %	98	100	$ 219	$ 2.19
Gallium nitrate	$Ga(NO_3)_3 \cdot xH_2O$	≤ 27 %	99.9	100	$ 805	$ 8.05
Samarium nitrate	$Sm(NO_3)_3 \cdot 6H_2O$	34 %	99.9	100	$ 195	$ 1.95
Samarium acetate	$Sm(C_2H_4O_2)_3 \cdot xH_2O$	≤ 45 %	99.9	100	$169	$ 1.69
Lanthanum nitrate	$La(NO_3)_3 \cdot 6H_2O$	32 %	99.99	500	$ 463	$ 0.93
Lanthanum nitrate	$La(NO_3)_3 \cdot xH_2O$	≤ 41 %	99.9	500	$ 220	$ 0.44
Lanthanum hydroxide	$La(OH)_3$	90 %	99.9	250	$ 114	$ 0.46
Praseodymium nitrate	$Pr(NO_3)_3 \cdot 6H_2O$	33 %	99.99+	25	$ 380	$ 15.20
			99.9	250	$ 240	$ 0.96
Dysprosium nitrate	$Dy(NO_3)_3 \cdot 5H_2O$	37 %	99.9	100	$ 125	$ 1.25
Erbium nitrate pentahydrate	$Er(NO_3)_3 \cdot 5H_2O$	37.7 %	99.99+	50	$252	$ 5.04
			99.9	100	$180	$ 1.80
Erbium acetate hydrate	$Er(C_2H_3O_2)_3 \cdot xH_2O$	≤ 48 %	99.9	50	$140	$ 2.80
Holmium acetate hydrate	$Ho(C_2H_3O_2)_3 \cdot xH_2O$	≤ 48 %	99.99	10	$133	$ 13.30
Ammonium bromide	NH_4Br	81.6 %	99+	500	$ 60	$ 0.12
			99.99+	250	$ 189	$ 0.76
			99	500	$ 33	$ 0.07
Sodium hydroxide	NaOH	57.5 %	99.998	250	$ 173	$ 0.69
			98	1000	$ 40	$ 0.04

Table 4. Data on composition, purity and cost of chemicals for radioisotope production for CTTC.

Chemical Name	Chemical Formula	Wt % Element of Interest	Purity (%)	Mass (g)	Price (CAN $)	Price ($/g)
Sodium carbonate	Na_2CO_3	43.4 %	99.5+	500	$ 52.70	$ 0.11
			> 99.95	500	$ 71	$ 0.14
Potassium carbonate	K_2CO_3	56 %	99.99	250	$ 184	$ 0.74
Potassium bicarbonate	$KHCO_3$	39 %	99.99	250	$ 185	$ 0.74
Potassium nitrate	KNO_3	39 %	99.5	100	$ 106	$ 1.06
			99+	500	$ 63	$ 0.13
Potassium hydroxide	KOH	71 %	99.99	500	$ 252	$ 0.50
			85+	500	$ 30	$ 0.06
Copper nitrate	$Cu(NO_3)_2 \cdot 2.5H_2O$	27 %	99.99	250	$ 183	$ 0.73
			98	500	$ 95	$ 0.19
Gold trichloride	$AuCl_3$	65 %	99	5	$ 607	$ 121.40
			99.99+	1	$ 184	$ 184.00

5. DETERMINE AVAILABILITY AND COST OF AN APPROPRIATE SHIELD FOR TRANSPORTING UP 200 MCI

Of the radionuclides listed in Table 1 ^{24}Na has the most energetic, and hence penetrating, gamma-rays (at 2.754 MeV and 1.368 MeV, with gamma-yields of 99.94 % and 100 %, respectively). Consequently, when considering a shield that would be appropriate for "transporting up to 200 mCi of a single radioisotope" ^{24}Na is the 'worst-case' scenario.

To transport 200 mCi of ^{24}Na as a Yellow II category shipment the dose rate at 1 m is required to be $\leq$ 1.0 mR h^{-1}. The thickness of lead required to reduce the dose rate due to 200 mCi of ^{24}Na to $\leq$ 1.0 mR h^{-1} would need to be of the order of 20 cm[6]. A shield, with a minimum of 20 cm of lead around a 5 cm long standard SLOWPOKE irradiation vial, would weigh approximately 645 kg (~1400 lbs). Such a shield could not be manhandled and would need to be fixed in the back of a transporting vehicle (*e.g.*, truck). A certified Type A container, suitable to transport 200 mCi of ^{24}Na from the University of Alberta to Suffield as a Yellow II category shipment, together with certification documentation and blueprints, would cost ~$5350 (including GST).

If the 200 mCi of ^{24}Na was transported as a Yellow III shipment a much smaller shield could be employed. A certified Type A shipping container built by Ronan Engineering, Toronto for the CNSC, and recently used to ship 120 mCi ^{64}Cu from the University of Alberta SLOWPOKE Facility to CFB Suffield, cost $2150. This shield has a 5 cm thick lead wall, weighs ~55 kg, and can ***easily*** be manhandled by two people (and moved if necessary by one person). Such a shield could be used to ship 200 mCi of ^{24}Na as a Yellow III package.

For the shipment of relatively small (*i.e.*, $\leq$ ~ 20 mCi) radioactive sources to the CTTC at Suffield, a certified Type A overpack container (10 gallon steel drum), that can easily accommodate an inner shield (wall thickness up to ~ 7.5 cm), can be purchased for less than

[6] With no shielding, the dose rate for gamma radiation at 1 m is given by 0.5CE R h^{-1} (where C = activity in Ci and E = total gamma energy per disintegration), which for 200 mCi ^{24}Na equates to ~412 mR/h @ 1 m.

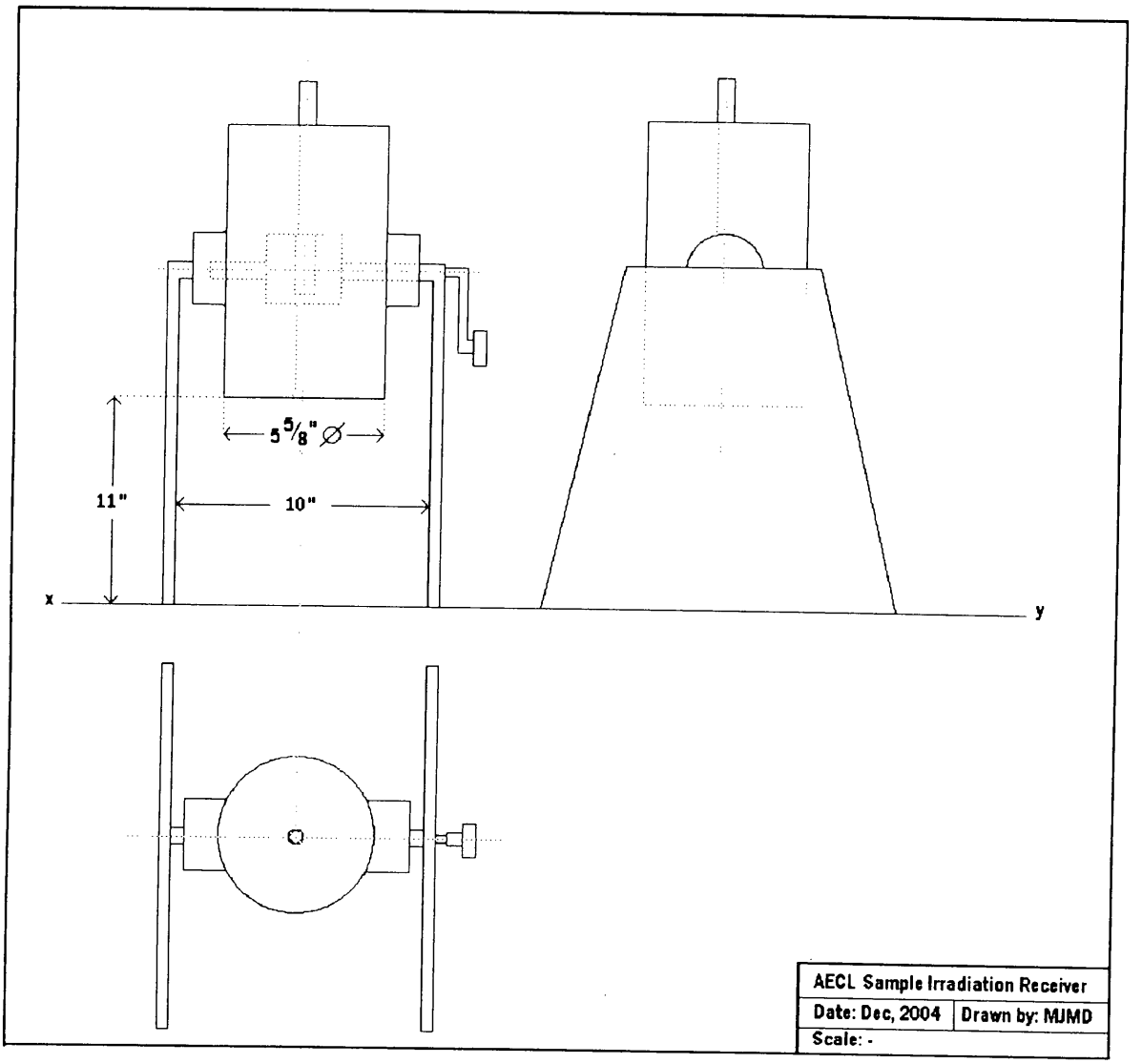
$200. There would be an additional charge for the lead shield, the cost of which would depend, in part, upon the wall thickness.

As can be seen certified type A shipping containers are commercially available and depending upon the decision whether to ship radioisotopes with an activity of ~ 200 mCi (or more) as Yellow II or III shipments the cost of a shield will range between $2200 to $5400. For shipping smaller amounts of activity (*e.g.*, ≤ ~ 20 mCi) the cost of a certified container and shield would be < $500.

6. Design System To Transfer Samples From Reactor To Shield To Minimize Exposure To Personnel

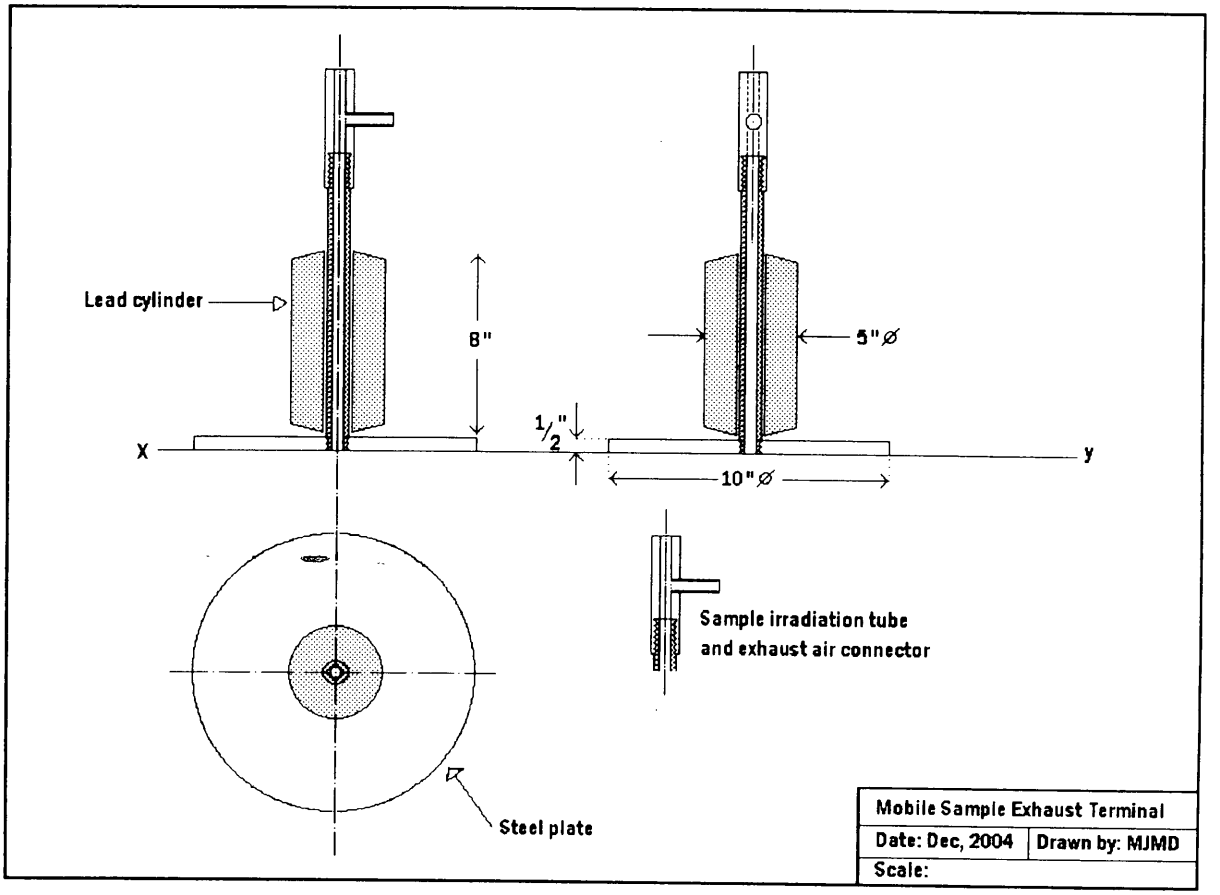
For relatively small (*i.e.*, $\leq \sim 20$ mCi) radioactive sources the irradiated sample(s) can simply and easily be transferred to the shipping container from the irradiation receiver (see Figure 1) by University of Alberta SLOWPOKE Reactor personnel. For highly active samples two alternatives are proposed (and have been used at the University of Alberta SLOWPOKE Facility previously). Firstly, a Type A shipping container/shield can be placed under the Pb irradiation receiver located within the reactor facility. Once ejected from the reactor into the irradiation receiver the sample can then be dropped from the receiver (Figure 1) directly into the shield, and the shield lid put in place and secured. Alternatively, using the apparatus in Figure 2, a sample can be blown directly from the reactor into a large shield (*i.e.*, too massive to be moved into the SLOWPOKE facility without mechanized equipment) located in the transporting vehicle parked immediately adjacent to the reactor facility. This approach has been utilized by the SLOWPOKE Facility on numerous occasions and minimizes handling, and any unnecessary exposure from highly radioactive sources. If a truck with a canopy is being used to transport radioactive material from the SLOWPOKE Facility to CFB Suffield, and this latter approach for transferring the radioactive material to the shield is to be employed, there must be sufficient headroom between the top of the shield to the roof of the canopy to accommodate the sample transfer tubing. If not, and the curvature of the tubing is too sharp, there is a risk that an irradiated sample could get trapped inline. Finally, the SLOWPOKE Facility has a mobile irradiation receiver (Figure 1) that can also be placed in the vehicle used for transporting the radionuclide(s) and the active source(s) transferred to this receiver before being dropped into the transporting shield. A frame would need to be built to support the sample receiver over the shield, but this cannot be designed until the dimensions of a shipping container are known.

Figure 1. AECL Sample Irradiation Receiver.



(not to scale)

Figure 2. Apparatus used to blow irradiated sample directly into a large shield in vehicle parked adjacent to SLOWPOKE Facility.



7. DETERMINE WHAT ADDITIONAL EQUIPMENT MUST BE PURCHASED IN ORDER TO MINIMIZE POSSIBLE INTERRUPTIONS IN SRPS FOR CTTC.

As evidenced by the fact that the University of Alberta SLOWPOKE Facility has produced radioisotopes for training purposes at CFB Suffield on a number of occasions during the past 24 months, and that the Facility routinely produces radioisotopes for industry (often in 100 – 300 mCi lots, and in some instances up to 1 Ci) the majority of the necessary infrastructure to set-up and operate the SRPS is already in place. Given the resources that go into the organization, planning and execution of a radiological training exercise at the CTTC, it is appreciated that a reliable source of radioactive materials (*e.g.*, the SRPS at the University of Alberta SLOWPOKE Facility) is essential to the success of those training exercises utilizing short-lived radioisotopes. Consequently, all reasonable steps need to be taken to minimize possible interruptions in the SRPS supply of radioisotopes for CTTC use.

When considering what factors could lead to an interruption in the SRPS for CTTC two main possibilities come mind, namely:

- lack of available personnel to operate the reactor
- reactor is not operational due to either:
    - failure of a component in the reactor console
    - failure of a component in the reactor (*e.g.*, flux monitor, thermocouple, control rod cable)

Given that the University of Alberta SLOWPOKE Facility currently has four CNSC-licenced reactor operators the likelihood of there not being an operator available to run the reactor and irradiate samples is extremely improbable. This is especially the case if there was some lead-time regarding the need for the production of radioisotopes for an exercise. Given the planning that goes into a radiological training exercise it is inconceivable to imagine that DRDC personnel would not discuss and arrange their radioisotope needs with SLOWPOKE personnel well ahead of time, thus ensuring the availability of a reactor operator.

Given the unlikelihood of there not being a reactor operator available the most probable cause of an interruption in the SRPS for CTTC would be that the reactor could not be operated. While such a scenario is improbable, it is not impossible because one is dealing with electro-mechanical equipment/systems in many instances. In particular, the reactor console, while relatively straight-forward electronically, is made-up of numerous electrical components (*e.g.*, power supplies, amplifiers, timer units, chart recorders, *etc.*) which can fail. Routine reactor maintenance, which includes the testing of many reactor console components, is performed weekly. However, electro-mechanical components do fail, and might be considered more likely to do so with increasing age. Failure of a component would most likely make the reactor non-operational until the necessary repairs were made. In a university setting lack of an electronics technician to diagnose and repair a fault would rarely be the cause of a significant delay in getting the reactor operational. The most likely cause of a significant delay in getting the reactor back operating would be the difficulty in getting the required components to carry out the necessary repairs. The University of Alberta SLOWPOKE reactor still has its original console which is 28 years old (though some components have been repaired or replaced). One possible way to minimize the likelihood of an interruption to the SRPS for CTTC would be to replace the existing reactor console with the new console (SIRCIS designed and used at the SLOWPOKE Reactor at the Royal Military College in Kingston, Ontario. One of the fortes of the new console is its modular nature and the ease with which components can be swapped if there is a malfunction in a component. A major drawback in replacing the existing console is the cost of a new console which at ~ $120,000 is not insignificant.

An additional component of the operation of the SLOWPOKE reactor is the radiation monitoring system that includes a reactor, area, and deionizer column radiation detector and local and remote alarm system. The reactor operating licence limits the operation of the reactor is the reactor and/or area alarm systems are not functioning properly. Repairs to the radiation monitoring system have been more frequent in recent years. Based on a recent quote the cost to replace the existing alarm system with a Rotern MediSMARTS Area Monitoring System would be $25,000.

In regards to minimizing any possible interruptions in SRPS for CTTC due to a failure in a component in the reactor the main concern here is not in the availability of a replacement component but lies in arranging for the necessary repair(s) to be made. Any operation that involves opening the reactor vessel can only be performed by a CNSC authorized reactor engineer licensed to providing nuclear maintenance services to the reactor.

Finally, running out of fuel and/or fission product poisoning of the fuel are also possible reasons for the reactor not being operational. However, with reasonable assumptions, current calculations estimate that the remaining life of the University of Alberta SLOWPOKE Reactor fuel is ~30 years.

8. COSTS FOR CONSTRUCTION AND OPERATION OF SRPS

As mentioned in the previous section the majority of the necessary infrastructure to set-up and operate the SRPS is already in place. However, some additional equipment would need to be purchased and/or built to operate the SRPS effectively and to minimize potential exposure to personnel. Furthermore, there are the costs associated with the operation of the SRPS.

The author has identified four main areas in this regard, namely:

a. radiation survey equipment
b. certified Type A shipping containers
c. consumables
d. radioisotope production costs

Each of these components is discussed in more detail below.

a. Radiation Survey Equipment

i) A calibrated survey meter, for determining dose rates, is legally required for TDG (Transport of Dangerous Goods) purposes, *e.g.*, for assessing the classification and Transport Index (TI) of the shipment. It is also required that the survey meter be calibrated annually to ensure its accuracy. A basic survey meter with an analog scale, such as the Ludlum Model 3 meter, with an energy-compensated GM detector, costs about $1100 (excluding GST). A unit with a digital readout such as the Ludlum Model 2241 with an energy-compensated GM detector is $2000 (inclusive of shipping and handling, but excluding GST). However, there is typically a problem with the accuracy of this detector-type when determining dose measurements from radionuclides emitting high-energy gamma-rays above ~ 1.25 MeV (*e.g.*, ^{24}Na, ^{72}Ga, ^{56}Mn, ^{140}La). A possible alternative to the Ludlum system is the Automess 6150AD5 dose rate meter, which has an energy range of 45 keV - 3 MeV, and costs about $2500 (excluding GST). Alternatively, compared to an energy-compensated GM tube more

accurate readings from high-energy gamma-ray emitting radionuclides are generally attainable with an ion chamber detector. Such meters are more expensive than the Ludlum survey meters but as already stated are generally more accurate when measuring dose rates due to high-energy gamma-rays. The Eberline RO-20 ion chamber is currently $2310 (including shipping and handling, but excluding GST).

In summary, the cost of a suitable survey meter for covering the energy range of the radionuclides envisaged (listed in Table 1) would be between $2300 and $2600 (excluding GST).

ii) A dose calibrator would be a very useful piece of equipment for confirming the actual activity of irradiated samples. When requested to produce a specific activity of a particular radioisotope (and compound) personnel at the facility calculate the mass of the chemical involved, the irradiation time and flux required, *etc.* to produce the requested activity. The calculations involved utilize data with some varying uncertainty associated with them *e.g.*, uncertainties due to possible self-shielding, inaccuracies in nuclear data, inexact value of neutron flux, and the thermal to epithermal neutron components, *etc.* A dose calibrator (similar to those used in nuclear medicine, for example) for quantifying the activity of specific radionuclides would be extremely valuable for confirming these calculations by empirically determining the activities. This would be particularly useful where the accuracy of the produced activity of the radionuclide in question is of importance (*i.e.*, when it is to be used to check the response of particular radiation measuring/monitoring equipment). An instrument such as the Capintec CRC 15R or the CRC 127R, would be suitable for this purpose. The cost of these instruments is $8425 and $7840, respectively (including shipping and handling, but excluding GST). In addition there would be an annual charge of about $60, to check the accuracy of the calibrator (for QA/QC purposes).

b. Certified Type A Shipping Containers

As noted in the section assessing the availability and cost of an appropriate shield for transporting up 200 mCi of a radioisotope, the cost of a commercially available certified type A shipping container would depend upon the whether shipment of radioisotope would be as a Yellow III or II package. The cost of an appropriate shield would be about $2200 and $5400, respectively. For shipping smaller amounts of radioactivity (*e.g.*, ≤ ~ 20 mCi) the cost of a certified container and shield would be < $500.

c. Consumables

The only consumable of significance in the operation of the SRPS for CTTC would be the chemicals irradiated to produce the desired radioisotopes. The cost of the chemicals would depend upon the number and purity of the chemicals purchased, and would in large part be governed by the requirements of the CTTC (*i.e.*, variety of radioisotopes utilized). The cost to purchase the stock chemicals to produce the radionuclides ^{24}Na, ^{42}K, ^{64}Cu, ^{82}Br, ^{187}W, ^{198}Au, ^{56}Mn, ^{72}Ga, ^{153}Sm, ^{140}La, ^{165}Dy, ^{171}Er, ^{166}Ho and ^{142}Pr would be about $3600 (see Table 4), excluding GST. In most instances the stock chemicals would last for tens of production runs for each radioisotope and would essentially be a one-time initial cost. This cost would reduce to ~$1900 if Au and the REEs were excluded from consideration, and to ~$1100 if Ga was also excluded.

d. Radioisotope Production Costs

There are a number of factors to consider when calculating the cost to produce a given activity of a particular radioisotope. The most significant of these are the neutron flux employed in the irradiation, the irradiation time required to produce the required activity, and finally an assessment of the risk, costs, and implications associated with an accidental spill of an active source and the resulting contamination and possible exposure.

Because of variations in the natural isotopic abundance of the elements, together with the differing nuclear properties of the nuclides (*e.g.*, neutron cross-section, half-life, *etc.*) some

elements, specifically their nuclides, activate more readily than others. Consequently, all other factors being equal, some elements need to be irradiated for a longer period of time than others to produce a particular amount of radioactivity. Similarly, the choice of chemical compound affects the amount of radioactivity that can be produced, and hence the irradiation time necessary. For example, to produce ^{42}K one could irradiate potassium hydroxide (KOH), potassium carbonate (K_2CO_3), or potassium nitrate (KNO_3). The amount of potassium in each of these compounds is 71 %, 56 % and 39 %, respectively (see Table 4). Therefore, other factors being equal, one would need to irradiate a sample of potassium nitrate almost twice as long (1.82 times) as the same mass of potassium hydroxide to produce the same ^{42}K activity. (Alternatively, one could produce the same ^{42}K activity by irradiating the same mass of KNO_3 as KOH, but at 1.82 times the neutron flux used to irradiate the KOH.)

Of the radioisotopes listed in Table 3 it would be possible to produce 100 mCi on-site at the CTTC at Suffield (assuming a decay period of 16h to permit transportation and overnight storage) of the following radioisotopes: ^{24}Na, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho and ^{198}Au. Because of the low isotopic abundance of ^{41}K (the precursor of ^{42}K) the maximum activity of ^{42}K that could readily be produced using the University of Alberta SLOWPOKE Reactor is ~25 mCi. Similarly, the low isotopic abundance and neutron cross-section of ^{170}Er (the precursor of ^{171}Er) limit the activity of ^{171}Er that could be produced and delivered to Suffield to about 10 mCi (following a decay period of 16 h). Because of the short half-lives of ^{165}Dy and ^{56}Mn 100 mCi of each radioisotope could be supplied on-site at Suffield mid-afternoon (~2:00 PM) assuming it was collected from the SLOWPOKE Facility in Edmonton at ~9:00 AM the same day (*i.e.*, transportation time of 5 h). As noted earlier the initial activity of these two radioisotopes at the time of departure from the University of Alberta SLOWPOKE Facility would be about 441 and 383 mCi, respectively, and because of the high energy gamma-ray emissions of ^{56}Mn some consideration as to the adequacy of the shipping shield used to transport the ^{56}Mn would be needed.

Finally, while difficult to quantify, there are risks associated with the production and handling of large amounts of radioactivity. For example, in the unlikely event that a spill was

to occur at the SLOWPOKE laboratory while producing or transferring a radioactive source for DRDC it would have significant ramifications on SLOWPOKE operations and costs associated with the clean up of the resulting contamination. Obviously the implications of a spill associated with a 1 mCi source are far less significant than with a 100 mCi source!

Currently, the production costs for 100 mCi of any of the following radioisotopes: ^{24}Na, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{165}Dy and ^{56}Mn (conditions as described on page 31) would be of the order of $1800 - $2200 per radioisotope.

To produce 10 mCi of any of the following radioisotopes: ^{24}Na, ^{42}K, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{171}Er, ^{165}Dy and ^{56}Mn (conditions as described on page 31) would be $400 - $500 per radioisotope (with a reduction for the production of two or more radioisotopes).

To produce 1 mCi of any of the following radioisotopes: ^{24}Na, ^{42}K, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{171}Er, ^{165}Dy and ^{56}Mn (conditions as described on page 31) would be ~$250 per radioisotope (with a reduction for the production of two or more radioisotopes).

The radioisotope production costs listed above include reactor time, personnel time (*e.g.*, for sample preparation, calculation of irradiation conditions, record keeping for the CNSC, assistance in sample transfer to shipping container, and licensed reactor operator time) and some minor consumables (*e.g.*, irradiation vials).

In this current estimation of the operating costs for the SRPS, the costs associated with shipping the radioisotopes from the University of Alberta SLOWPOKE Facility to the CTTC (by commercial courier or CFB Suffield personnel, for example) ***have not*** been included. These costs would be the responsibility of the CTTC DRDC.

Table 5. Costs for Construction and Operation of SRPS.

ITEM	COST	EXPLANATION / DESCRIPTION
Survey meter	$ 2300 - $2600	Calibrated meter required for monitoring and classifying radioactive shipments
Survey meter annual calibration	$ 55	Licence and shipping requirement
Dose Calibrator *e.g.*, - CRC 15R **or** - CRC 127R	 $ 8425 $ 7840	For the empirical determination of the activity of samples (and confirmation of calculations)
Type A Shield (for ≤ 200 mCi source)	$2200 - $5400	Price range dependent upon whether radio-isotope shipped as a Yellow III or II package.
Type A Shield (for ≤ 20 mCi source[s])	$ 500	Shield for shipping smaller amounts of radio-isotopes
Chemicals	$1100 - $3600	Depending upon the number and purity of chemicals purchased
Tongs	~ $ 50	For handling radioactive samples
Sub Total:	**~ $ 14,000 - $20,630** (excl. GST)	

RADIOISOTOPE PRODUCTION COSTS		
100 mCi source*	$1800 - $2200 per radioisotope	^{24}Na, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{165}Dy and ^{56}Mn
10 mCi sources*	$400 - $500 per radioisotope	^{24}Na, ^{42}K, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{171}Er, ^{165}Dy and ^{56}Mn
1 mCi sources*	~$250 per radioisotope	^{24}Na, ^{42}K, ^{82}Br, ^{64}Cu, ^{72}Ga, ^{187}W, ^{153}Sm, ^{140}La, ^{76}As, ^{142}Pr, ^{166}Ho, ^{198}Au, ^{171}Er, ^{165}Dy and ^{56}Mn
Sub Total:	**Dependent on activity and no. of radioisotopes** (excl. GST)	

* - conditions as described in 'Radioisotope Production Costs' Section 8. IV above.

9. ANNEX A: STATEMENT OF WORK

Title:

Development of a Short-lived Radioisotope Production Service (SRPS) for CTTC at University of Alberta SLOWPOKE Reactor Facility.

Background:

An integral feature of the radiological training facility at Counter Terrorism Training Centre (CTTC), Defence Research and Development Canada (DRDC) Suffield is the capability to work with unsealed radioactive chemical compounds (primarily in liquid form). The preferred radioisotopes for such work this are those with short half-lives in a form that is, of course, water-soluble.

During the course of the NATO Exercise Prototype Response at Suffield, DRDC Ottawa used three such radioisotopes (24Na, 42K and 64Cu) in mCi quantities that were produced at the University of Alberta SLOWPOKE Facility.

For CTTC work activities of the order of up to 100 mCi are envisaged. A facility to do this on a routine basis is needed. This contract will achieve this design, and perform a rough costing.

Tasks :

The Contractor will perform the following tasks:

i. Consult with the Scientific Authority and thence provide a list of those radioisotopes and applicable chemical compound that will:
   a) meet the needs of CTTC and
   b) can be readily produced in the SLOWPOKE reactor.
   The prospective isotopes include, but are not limited to, 24Na, 82Br, 64Cu and 42K.

ii. Consult with the Scientific Authority and finalise the isotopic and chemical choices and irradiation criteria.

iii. Determine the availability and cost of an appropriate shield for transporting up 200 mCi of a single radioisotope OR if no commercial shield is available, design an appropriate shield for transporting up to 200 mCi of a single radioisotopes; and in either instance also design a transfer system (from reactor to shield) that will minimize dose to personnel.

iv. Determine what additional equipment must be purchased in order to minimize any possible interruptions in the radionuclide production service for CTTC.

v. Give costs for construction and operation of SRPS.

Location of the Work :
Most work will be performed at the Contractor's premises. Travel to DRDC Suffield for discussions may be necessary.

Deliverables :
Reports: 5 copies of final report at completion of contract.

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